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Technology Days in the Government
Mirror Development and Related Technologies
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OPTICAL APPLICATIONS OF NANO-LAMINATES

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Nano-Laminates

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OPPORTUNITY!

To enable a new class of optical structures that are ultra-lightweight, dimensionally stable, resistant to environmental effects, have low cost and are fast to manufacture.

What are Nano-Laminates?

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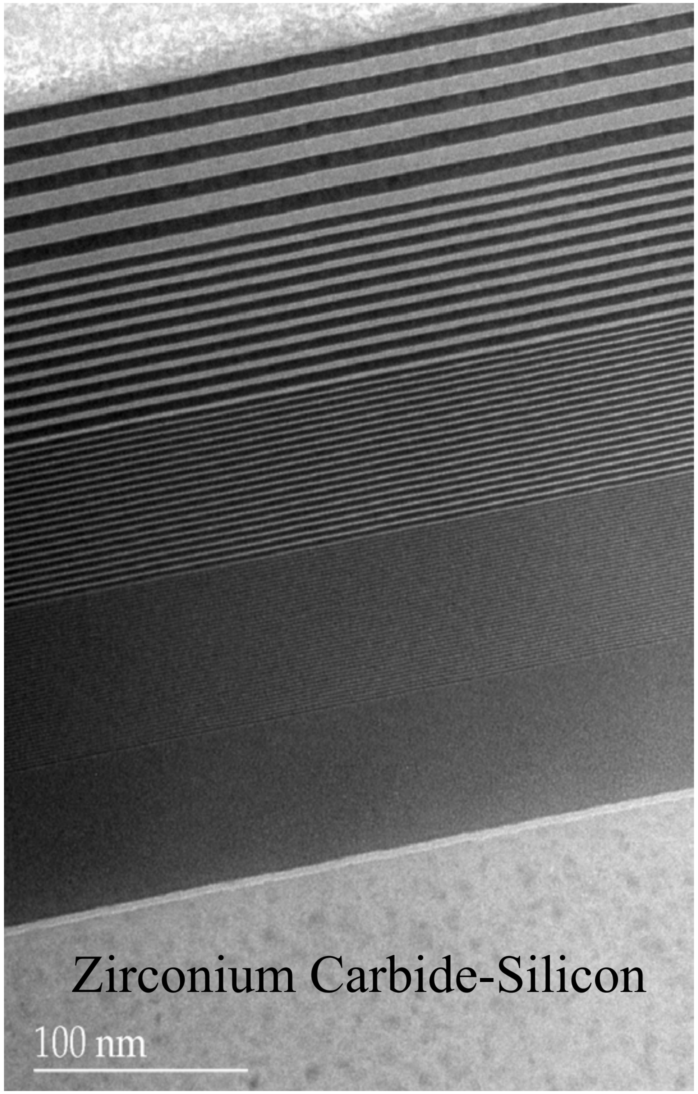

- Nano-Laminates are man made layered structures synthesized atom by atom using sputter deposition technology

- A Cross-section Transmission Electron Microscopy image of a multi-period ZrC/Si Nano-Laminate fabricated by sputter deposition for X-ray Optic Applications is shown here

- The thickest dark ZrC layers are 5.77nm (57.7 Å) thick. The thick Si layers are 6.73nm (67.3 Å) thick.

- The thinnest layers (ZrC - 0.36nm/3.6Å and Si - 0.42nm/4.2 Å) are not observable in this Lower magnification image but are seen at higher magnifications

Nano-Laminate Technology Produces Materials Having Unique Engineerable Properties

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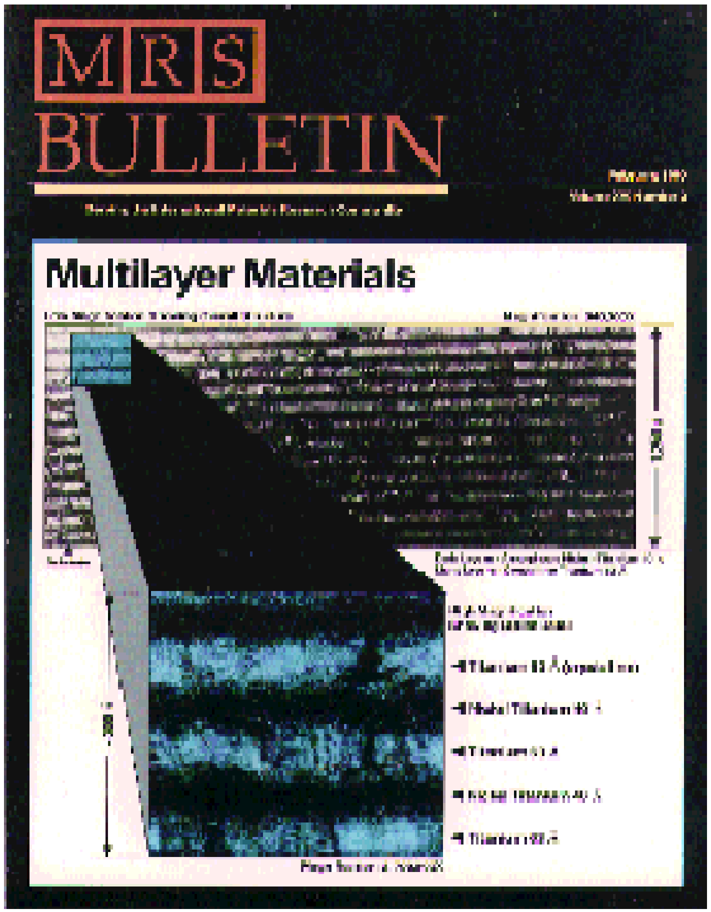

- Near theoretical limit in strengths and hardness for *macroscopic* materials

- ***Strength Combined with:***
  - ***Corrosion resistance***
  - ***Erosion resistance***
  - ***Fracture toughness***
  - ***High Surface Quality*** $\sigma < 1$ *nm rms*

Nano-Laminate Applications

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- ***Ultra-High Strength Materials***
- ***Magnetic Transducers - GMR_***
- ***High Performance Tribological Coatings***
- ***EUV, Soft X-ray and X-ray Optics___***
- ***Coatings for Gas Turbine Engines***
- ***Microcircuit Lithography Development____***
- ***High Performance Visible Optics***
- ***High Performance Capacitors_***
- ***Integrated Circuit Interconnects***
- ***New*** Materials and ***New*** Devices Based on the ***Chemical & Structural Control*** Available with Engineered Nano-Laminate Materials_
- ***Basis for New Manufacturing Strategy***

Nano-Laminate Materials

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- Nano-laminates are a new class of that are capable of approaching theoretical limits of strength.
  - This property is important because high specific strength produces a more durable material at smaller cross sectional areas and supports surface quality.
  - Additionally, as metals typically have stiffness larger than that characteristic of glasses, metallic nano-laminate materials will perform better as thin foil structures.
- Nano-laminates are synthesized using atom by atom physical vapor deposition sequential magnetron sputtering.
  - Elemental materials, alloys or compounds are sputtered producing individual layers having a thickness ranging from a single monolayer (0.2 nm) to hundreds of monolayers (>500 nm)
  - Macroscopic sample thickness up to 400 μm has been demonstrated. Nano-laminates allow direct and perfect replication off of a master tool

Features of Nano-Laminate Mirrors

- Nano-Laminate materials result in very low areal density mirrors
  - Areal density 0.174 kg/m^2 to 0.8 kg/m^2 for 0.1mm (100μm) thick structure
  - Targeted areal density ≈ 2 kg/m^2 with in-plane actuators

  - They can be rapidly manufactured by replication using precision master tooling at low cost
  - Over fifteen 0.25 meter mirrors and ten 0.5 meter diameter fabricated made to date off precision tools

  - Nano-Laminate synthesis time is independent of diameter of optic
  - A 100 μm thick optical nano-laminate structure takes less than 72 hours to manufacture

Precision Replication

- Direct application to optical wavelengths
  - They will enable deployable telescope systems with applications from the visible to infrared wavelengths. Adaptive capabilities will be required for the highest level of performance
  - Nano-Laminate Surface roughness has been demonstrated to directly correlate to master substrates roughness
  - A sputter deposited 25 μm thick foil deposited on a super polished substrate, 0.02 nm rms and 0.14 nm PV, had a 0.05 nm rms roughness and 0.18 nm PV on the "to substrate surface" and 0.2 nm rms roughness and 0.29 nm PV roughness on the "to ambient" surface
- This technology is applicable to flat, spherical and aspheric large optics for both ground and space based applications

Scanning Tunneling Microscopy

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Scanning tunneling microscopy measurements of σ, the rms surface roughness, show that the interface deposited in contact with the substrate exactly replicates the substrate surface rms. The best result to date is 0.3 nm rms achieved using a super polished fused silica substrate - rms = 0.22 nm.

Measurements of the rms surface roughness of the final deposition surface of a 38.4 μm thick 40 nm period copper-zirconium nano-laminate deposited onto a super-polished fused silica substrate (σ - 0.1 nm) using scanning tunneling microscopy are summarized here.

Scan Length	σ (rms) nm	Area $(\mu m)^2$
1μm	3.415	1.008
1μm	5.458	1.015
1μm	4.269	1.044
1μm	3.937	1.032
1μm	3.533	1.039
2μm	4.492	4.057
2μm	3.89	4.05
5μm	4.73	25.132
5μm	4.693	25.137

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Nano-Laminate Mechanical Properties

Material	(Xtal/Xtal) Period (nm)	Hardness (meas.)	Strength	Strength Improvement Factor elevation [a,b]
Pt/Cr (Xtal/Xtal)	3.5	11.5 GPa	3.8 Gpa[a] 556 ksi	~10 X
304SS/Zr (Xtal/Am)	2.72	9.3 GPa	3.1 Gpa[a] 450 ksi	~8 X
Cu/Zr (Xtal/Am)	**40**	**2.7 GPa**	**≈1.1 GPa[b] 152 ksi**	**~5 X**
Cu/304SS (Xtal/Xtal)	2.0	5.2 GPa	1.68 Gpa[b] 243 ksi	~4 X
Cu/Monel	2.0	4.4 GPa	210 ksi[b]	~3.5 X

a Estimated from hardness measurements, b Measured in standard tensile tests (ε = 5 x 10–5/sec)

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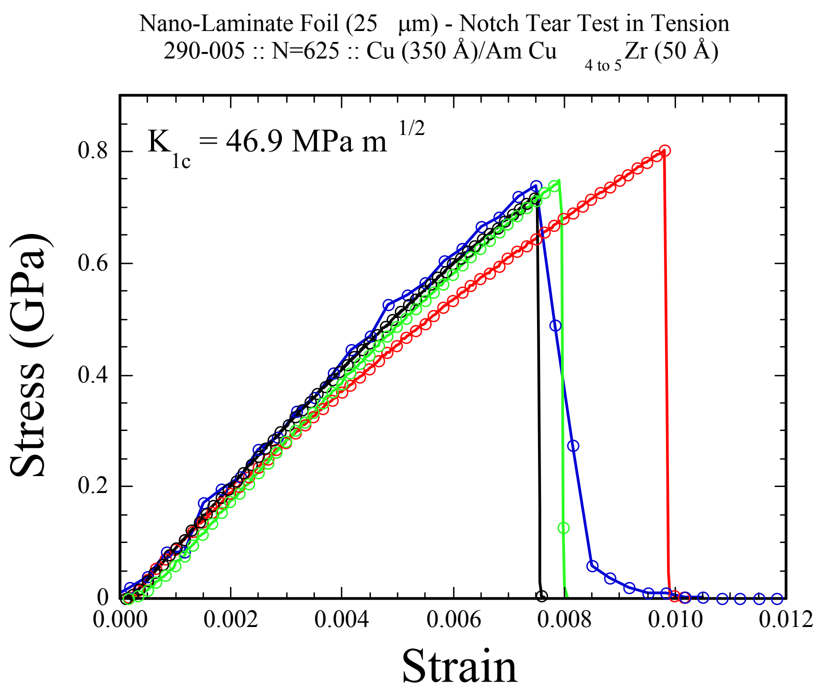
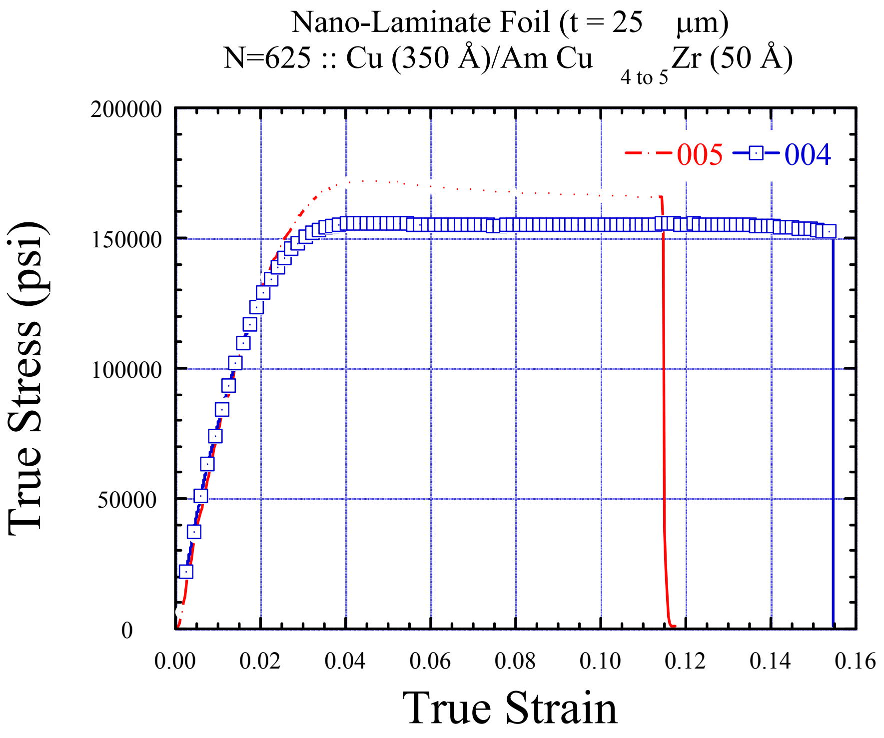
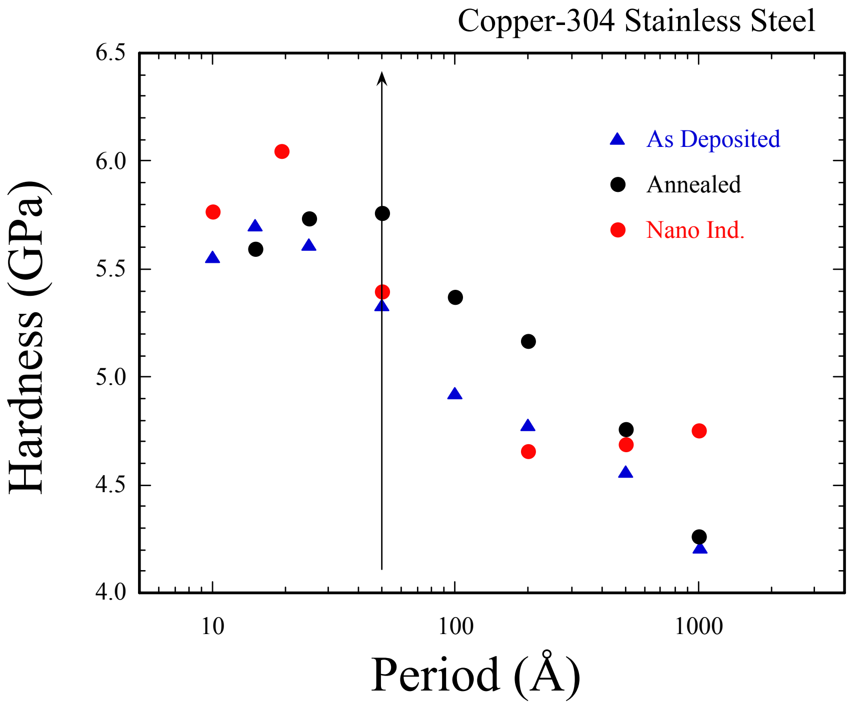
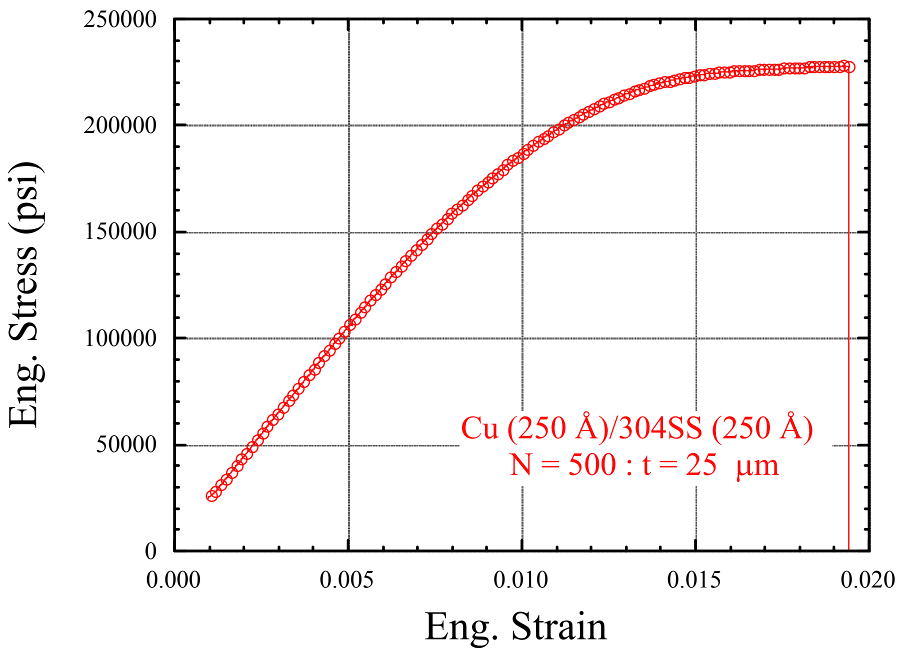
Mechanical Test Results for the Copper-Copper/Zirconium Nano-Laminate





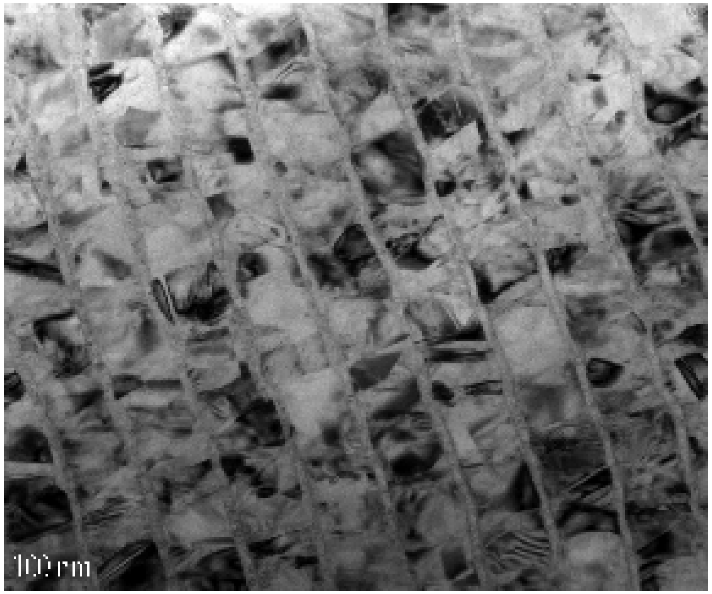
Mechanical Test Results for Copper-304SS Nano-Laminates





Nano-Laminate Mirror

TEM Cross section



Finished Mirror

50 cm diameter Cu/Cu_xZr_y nano-laminate

- Mult-layer metallic foils grown by sputter deposition with atomic-scale control
- Very thin, lightweight, flexible but stiff structures with excellent surface finish
- Controllable by mechanically attached actuators

Fabrication at the Nano-Scale Yields Unique Properties

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Nano-Laminate Materials are based on Materials Research/X-Ray Optics Heritage

Copper/Zirconium - Areal Density 0.8 kg/m^2
- Strength - 155 ksi
- Modulus - 13×10^6 psi
- Thermal Expansion - 12×10^{-6}/C

Material Properties can be Designed to improve

• Optical • Thermal • Mechanical - Performance •

- Higher Elastic Modulus to enable more effective Actuation for Figure Control
- Decreased Areal Density to reduce mass
- Decreased Thermal Expansion to Reduce Thermal Distortions
- Increased Thermal Stability

Material developed based on LLNL Materials Research Heritage

1. Expected Modulus 20×10^6 psi
2. Expected Areal Density: 0.65 kg/m^2
3. Expected Thermal Expansion: 2×10^{-6}/C
4. Thermal; Stability Substantially Increased
5. Strength > 200 ksi

Nano-Laminate Scaleup

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1.3 meter diameter, 0.1 micron rms surface Actuated Hybrid Technology Nano-Laminate (AHTM) Thin Shell Mirror

Technology Area	Technology Needs	Drivers	Limiting factor
Materials Development of Properties Database	▪ Develop materials systems reducing areal weight and enabling surface figure optimization via thermal reaction/ internal stress reduction on master tool before parting thin shell optic structure ▪ Thin shell optic structures thicker than 30 to 100 microns for mechanical stability	▪ Materials Science R&D ▪ Process demonstration	$/Time $/Time
Replication/Deposition of 1.3meter Nano-laminate Thin Shells	▪ Uniform deposition over large figured substrate areas ▪ Minimization of residual and Diff Thermal Expansion stresses in large surface area thin shell optic structures • Extend Thin Shell Optic foil parting technology to removal of very large area structures from tooling substrates	▪ Large deposition facility - Under Construction ▪ Demonstrate Process	$/Time
Tooling substrate development	▪ Need lightweight 1.3 meter master substrates to reduce thermal mass and to facilitate thin shell optic processing ▪ Potential material is "thin" /SiC/Foams supported by light weighted structures.	▪ Tool cost/ availability ▪ Radius of curvature of primary optic	$/time System design

Actuated Hybrid Mirror (AHM)

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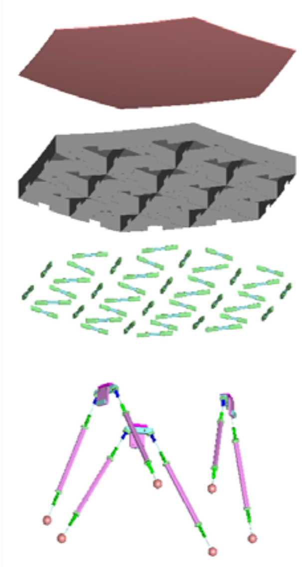
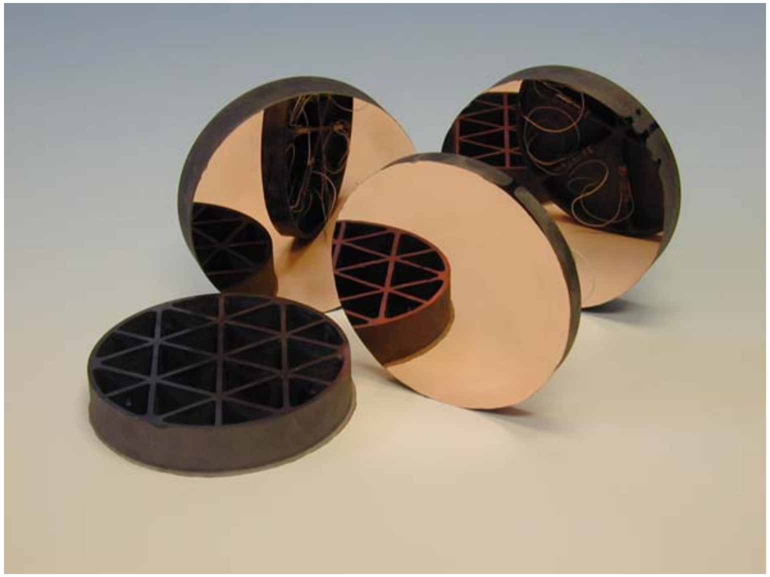
- The combination of distinct technologies
  - **Facesheet:** Nanolaminate foil (DOE/LLNL)
  - **Substrate/figure control:** Actuated silicon carbide (Xinetics, Inc. Devens MA)
  - **Metrology hardware and algorithms: W**avefront sensors (NASA/JPL)
- AHM represents a stepping stone to a future, all nanolaminate-based mirror system



Nano Laminate	0.4 kg/m²
SiC Substrate	4.8 kg/m²
Actuators	1.2 kg/m²
Bipods	0.4 kg/m²
Harness	0.2 kg/m²
Total	**7.0 kg/m²**



MEMS + Nano-Laminate technolog could lead to a new generation in adaptive optics

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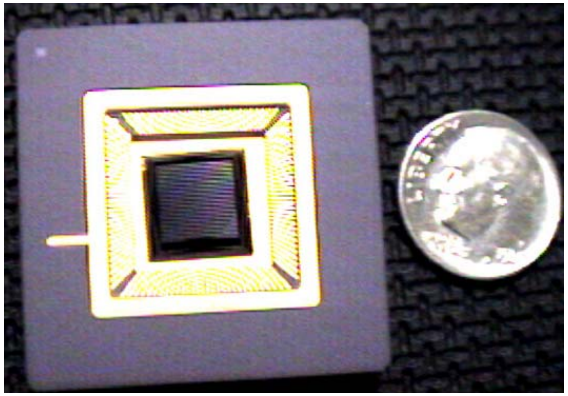
Current adaptive optics systems are large and expensive due to available wavefront corrector technology

- The standard wavefront corrector is a deformable mirror consisting of a thin stiff plate with a set of ceramic actuators attached to the back
- Typical conventional deformable mirror costs are (?) $1,000 per actuator

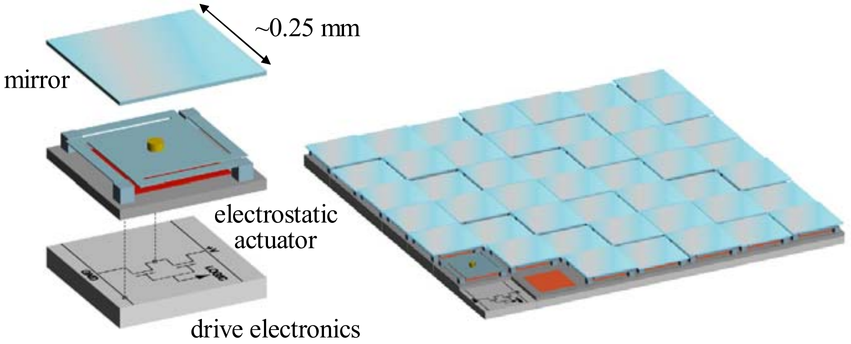
- Small low-cost deformable mirrors can now be fabricated with MEMS techniques for ~$1 per actuator

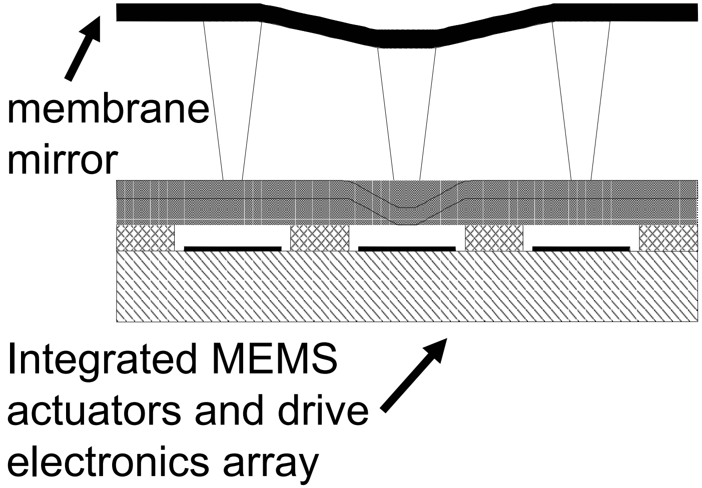


Large area-low residual stress-high strength- nano smooth nano-laminate foils can provide engineerable membranes for MEMS actuated adaptive optic systems

New membrane mirror and MEMS technologies could be integrated to produce a new class of flexible optics

- LLNL has coordinated efforts to develop new MEMS spatial light modulator technology
- Current work emphasizes device architecture with integrated mirrors, actuators, and electronics
  - *scales to large numbers of phase control elements ($1x10^3$ - $1x10^4$).*





- These new approaches in integrated MEMS spatial light modulators can be combined with new LLNL membrane mirror technology.
  - *Replace individual mirror pixels with low-stress, high-quality membrane*
- New LLNL membrane technology has significantly enhanced characteristics for this application over previous work.
  - *Previous membrane approaches includes polysilicon, single-crystal silicon, highly doped silicon, and silicon nitride*

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Summary

- Nano-laminates are a new class of materials for optics enabling large actively controlled systems.
- They represent the **most mature nano-structured materials** available with the capability to approach theoretical limits strength representative of metallic materials.
- This approach to replicated optics reduces cost and time to delivery, and is scalable to large area optical surfaces.
- This enables a new class of thin shell optics that allows for precision actuation with projected areal densities less than 7 kg/m^2 including actuation.
- This technology is scalable to several meters in diameter and lends itself to rapid manufacture of precision replicated, low scatter optics.
- This technology when combined with electro-active actuation may be an enabling technology for ground based astronomy and many future NASA missions, such as Terrestrial Planet Finder.

Acknowledgement

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